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A Novel Mobility Management Scheme for Integration of Vehicular Ad Hoc Networks and Fixed IP Networks

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Abstract Integration of vehicular ad hoc network and fixed IP network is important to provide Internet connection and mobile data service for vehicles. However, the unique characteristics of vehicular networks, such as linear topology and constrained movements of vehicles, are not considered in the conventional mobility management schemes. Using conventional schemes, unnecessary management messages are generated and the connections to roadside-installed base stations are not fully utilized. As the results, bandwidth is wasted and data delivery ratio is not maximized. In this paper, we propose a novel mobility management scheme to integrate vehicular ad hoc network and fixed IP networks more efficiently. The proposed scheme manages mobility of vehicles based on street layout as well as the distance between vehicles and base stations. Utilizing the unique characteristics of vehicular networks, the proposed scheme has substantially less mobility management overhead and higher data delivery ratio. The proposed scheme is simulated by SUMO (a vehicular traffic simulator) and QualNet (a data network simulator). The simulation results show that the proposed scheme reduced the mobility management overhead up to 63% and improved the data delivery ratio up to 90%.

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1 Introduction

The emerging vehicular network has arisen a lot of attention recently due to its potential contributions to public transportation. As the goal of US Federal ITS (Intelligent Transportation Systems) program [1], wireless communication devices that are installed on vehicles or roadside-installed base stations are expected to help reducing collisions and relieving traffic congestions. For this purpose, FCC (Federal Communications Commission) has allocated 75 MHz of spectrum for Dedicated Short Range Communications (DSRC) used in ITS. The new MAC and physical specification for DSRC, developed by IEEE 802.11p group, defines enhancements on IEEE 802.11a to support ITS application. In [2–8], authors made efforts to explore the communication capability of vehicular networks. Projects like FleetNet [9], OverDRiVE [10] and CarTALK 2000 [11] were established to verify the concepts of vehicular networks. A couple of recent studies in [12–14] have been focusing on the evaluation of IEEE 802.11p standard.

The architecture of vehicular network, as shown in Fig. 1, include three primary components: Onboard Unit (OBU), Roadside Unit (RSU) and Backhaul network. OBUs are wireless devices that are installed on vehicles and RSUs are wireless devices that are installed on roadside base stations (BSs). A wireless device (on an OBU or a RSU) has the capability to communicate with another one directly when that

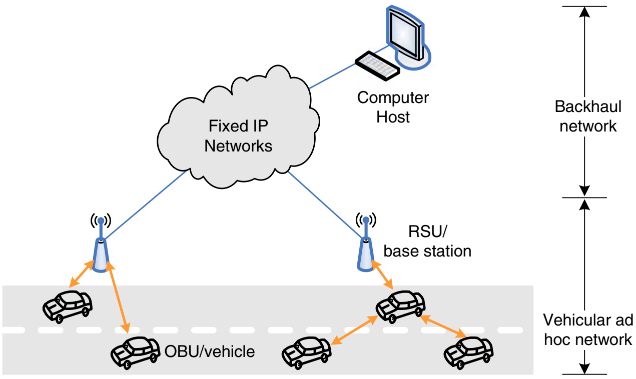


Fig. 1 The architecture of a vehicular network

wireless device is in its radio range. A set of wireless devices (on OBUs or RSUs) construct a vehicular ad hoc network (VANET). Via the VANET, vehicles can exchange messages with each other or with roadside-installed base stations by multihop (for simplicity, *vehicles* and *base stations* have the same meaning with *OBUs* and *RSUs* in this paper). Through base stations, which are connected to the backhaul network, vehicles can visit the fixed IP network. Based on this architecture, two types of applications are provided in vehicular networks: safety-relative applications and information-relative applications. Researchers discussed the communication schemes for security relative applications in vehicular ad hoc networks in [2, 5, 7, 15, 16]. Various proposals for information-relative applications are discussed in [3, 4, 6, 8, 17–20].

Information-relative applications, such as traffic management and visiting information querying, often involve both vehicular ad hoc networks and fixed IP networks. For example, a computer in the headquarter of a company could send a message to a vehicle on the road. A type of research on information-relative applications is to study the efficient scheme to manage the mobility of vehicles in vehicular ad hoc networks. Most existing schemes [8, 19, 20] are based on the conventional Mobile IP (MIP) [21] with a simple extension, where the last-hop wireless connection is simply replaced by a small k-hop multihop ad hoc network. Mobile nodes that are within k hops of a home/foreign agent register on the agent in order to send packets to or received packets from hosts in fixed IP networks, that have to be forwarded by the home/foreign agent. Other operations of mobility management are similar to those of the conventional Mobile IP. We call this type of mobility management scheme the *conventional Multihop Cell* scheme, where each base station sits at the center of the associated ad hoc network. However, the conventional Multihop Cell scheme does not consider the characteristics of vehicular networks and becomes inefficient.

This paper is inspired from the observation of unique characteristics of vehicular networks and aim to utilize them to reduce the management overhead thus improve data communication performance. We observed that movements of vehicles are constrained by the layout of the road, a linear-like topology (compared with the two-dimensional area in a general ad hoc network), and vehicles often move from one intersection to another intersection along the roads. The conventional Multihop Cell scheme has two problems in a vehicular network: (a) sending out unnecessary management messages and (b) failing to fully discover the connections between base stations and vehicles. Firstly, to search a destination vehicle, a base station broadcasts signaling messages in the associated ad hoc network within k hops. As the Fig. 2 shows, the signaling messages to the roads that the destination does not resided in will never reach the destination. These signaling messages increase the overhead unnecessarily. Secondly, only the base station where a vehicle has registered will discover connection with the vehicle, even though several base stations may have high probability to reach the destination vehicle. To address these problems, a novel Roadside Multihop Cell scheme is proposed in this paper for integrating VANET and fixed IP networks.

The proposed Roadside Multihop Cell is constructed in such a way that a multihop cell is between several adjacent base stations and base stations are at the entrances of a cell, as shown in Fig. 2. Essentially, the proposed Roadside Multihop Cell scheme manages vehicles according to street layout instead of the conventional two-dimensional area where mobile nodes can move freely. This scheme has following advantages. First, when searching a destination, a base station sends out signaling messages on the roads where the destination resides only. Second, multihop service

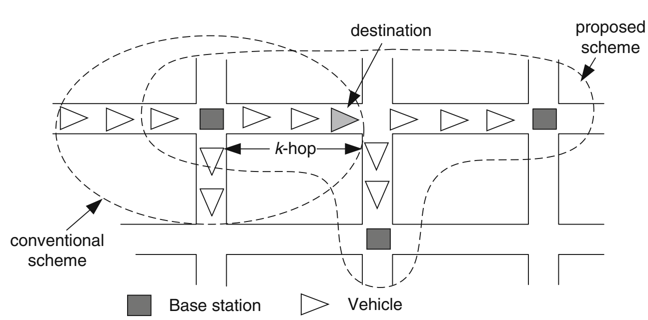


Fig. 2 The conventional Multihop Cell scheme vs. the proposed Roadside Multihop Cell scheme

announcement and registration operations are converted into single-hop operations, taking the advantage that base stations are at the entrances of cells. Third, a vehicle registers to a Roadside Multihop Cell, which is associated with several base stations.When searching a destination vehicle, all base stations of a Roadside Multihop Cell try to discover a path to the vehicle. These strategies reduce the management overhead and improve the connectivity in vehicular networks. Using the proposed scheme, the simulation results show that the data delivery ratio is improved up to 90% and the mobility management overhead is reduced up to 63% in our simulation results.

The contributions of this paper are summarized as follows.

- We propose a novel mobility management scheme for integration of VANET and fixed IP networks. The proposed scheme manages mobility of vehicles based on street layout instead of a general two-dimensional ad hoc network.
- The proposed scheme utilizes the information provided by vehicular network to reduce mobility management overhead.
- The proposed scheme allows several base stations that are close to a destination vehicle to discover the connection to the vehicle simultaneously. This operation improves the connectivity and data delivery ratio without redundant messages.

This paper is organized as follows. Related works is discussed in Section 2. In Section 3, system model of the proposed mobility management scheme is presented. The operations of the proposed scheme are described in Section 4. In Section 5, we analyze the improvement of connectivity using the proposed scheme. In Section 6, we evaluate the performance of the proposed scheme. Finally, the paper is concluded in Section 7.

2 Related work

Safety-relative applications, like collision avoidance and driving assistance, usually involve vehicular ad hoc networks only. Messages are exchanged in a small scope and required to be delivered in time. An overview of highway cooperative collision avoidance (CCA) is presented by Biswas et al. in [2]. Yang et al. design a protocol including congestion control policies, service differentiation mechanisms and methods for emergency warning dissemination in vehicular networks [5]. Little and Agarwal discuss how to propagate safety-related information such as local congestion and surface ice in certain directions [7]. The WAVE (Wireless Access in Vehicular Environment) technology that is under standardization as IEEE802.11p and IEEE P1609 is introduced by Hayashi in [15]. WAVE system is expected to provide stable operation, reliable communication and higher performance in the scenarios such as crossroad collision avoidance and front-tail collision avoidance. Bohm and Jonsson propose a communication system for safety-critical vehicle-to-infrastructure communication based on an extension to IEEE 802.11p to adapt the resources set aside for collision-free, safety-critical data traffic to the communication needs of vehicles [16].

To realize information-relative applications, vehicular ad hoc networks and fixed IP networks should be integrated and the mobility of vehicles should be managed. The architecture and functional requirements for the integration are presented in the white paper [22]. Ruiz et al. introduce the main challenges and design options that need to be considered for information-relative applications in vehicular networks. Wu et al. presented an approach for efficient and reliable data dissemination in vehicular networks despite the highly mobile, partitioned nature of these networks [3]. The proposed scheme combines the idea of opportunistic forwarding, trajectory based forwarding and geographical forwarding. Data dissemination in vehicular networks is also discussed by Zhao and Cao in [4], where they let a moving vehicle carries a packet until a new vehicle moves into its vicinity and forwards the packet. Seet et al. design a position-based routing scheme in a built-up city environment, which could use information like city bus routes to identify an anchor path with high connectivity for packet delivery to improve the data dissemination performance [6].

3 System model and rationales

In this section, assumptions and the system model of vehicular networks are presented at first. Then, we propose the concept Roadside Multihop Cell according to the characteristics of vehicular network.

3.1 Assumptions

Firstly, we assume that vehicles are able to determine the next road when they are approaching or have passed an intersection. This assumption is reasonable considering advances in GPS technologies, navigation systems, onboard sensors and intelligent vehicular devices. At an intersection with a base station installed, vehicles send their next road to the base station.

Vehicles that have wireless communication capability are also assumed to cooperate and forward messages for other vehicles. Vehicles are assumed to have enough power supply for wireless communications.

Base stations are assumed to have knowledge about other base stations in vehicular networks. This knowledge can be configured at the startup or retrieved via the backhaul network. The radio range of base stations and vehicles are assumed to be larger than the width of road. Typically, the radio range is at least 300 meters. This ensures that vehicles can communicate with a base station when they pass by the base station.

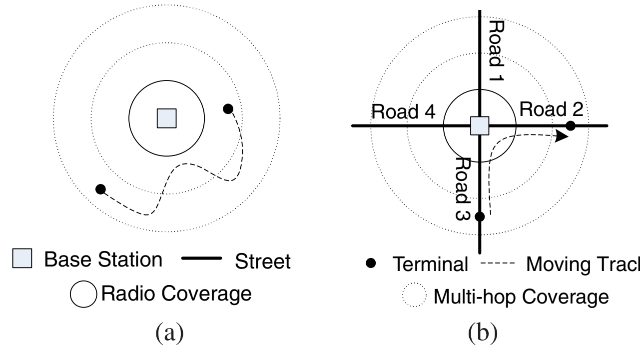


Fig. 3 Comparison of mobile nodes in general networks and vehicular networks. **a** General mobile nodes move freely in two dimensions. **b** Vehicles move along the roads

3.2 The model of vehicular networks

A vehicular network is modeled as a graph $G = (V, E)$, where the nodes in V represent intersections and the edges in E represent roads which connect intersections. An intersection may be a real road junction or a virtual intersection, which is a place on a road where a base station is installed. Intersections where base stations are installed are called informative nodes, while other intersections are called common nodes. The movement of vehicles in a vehicular network can be modeled as moving from an intersection to another intersection, along the road edges. A base station's radio range covers the road in its neighborhood. A vehicle in the radio range can communicate with the base station directly. Vehicles can also communicate with a base station via multiple hops by using communication protocols of ad hoc networks.

3.3 Directional Multihop Cell

In conventional Multihop Cell scheme, a cell is assumed to be a two-dimensional ad hoc network where a base station is installed at the center and mobile nodes move around the base station, as Fig. 3a shows. Intuitively, the base station manages its cell by broadcasting messages, within k hops, including the messages to announce services and the messages to discover the connection to a destination mobile node in the cell.

However, unlike general mobile nodes that can move freely in two dimensions, vehicles can move along the roads only. As Fig. 3b shows, a vehicle has to pass the intersection when moving from road 3 to road 2. Otherwise, the vehicle must use roads outside of this area. If the vehicle tells the base stations at the intersection which road it turns, as we assumed, the base station not only knows that the vehicle is in the neighborhood, but also has a more precise knowledge about which road it resides in. We define the Directional Multihop Cell to utilize such knowledge for mobility management.

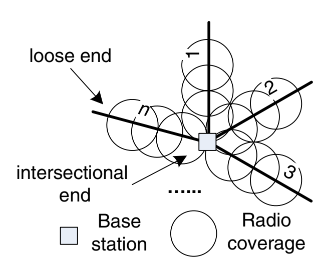
Definition 1 A k-hop Directional Multihop Cell is defined as a one-dimensional k-hop ad hoc network along a road that has at least one end at an intersection where a base station is installed.

As Fig. 4 shows, the end of a Directional Multihop Cell where a base station is installed is called an *intersectional end*, and the end where no base station is installed is called a *loose end*. At an intersection with n directions, there are n Directional Multihop Cells which merge at the intersection. We assign an ID for a base station and a number for a direction of the intersection where the base station is installed. A Directional Multihop Cell on a road $d (1 \leq d \leq n)$ at the intersection where the base station ID_{BS} installed is uniquely identified by $[ID_{BS}, d]$.

3.4 Roadside Multihop Cell

Adjacent Directional Multihop Cells can be combined together to form a Roadside Multihop Cell.

Fig. 4 Directional Multihop Cell



Definition 2 A Roadside Multihop Cell is constructed by adjacent Directional Multihop Cells that have a common loose end.

For example, in Fig. 5, Roadside Multihop Cell 1 (RMC_1) consists of (BS_1, 2), (BS_2, 1) and (BS_3, 1). These adjacent Directional Multihop Cells are put together and create a special ad hoc network where all entrances of the network have base stations installed. A base station may belongs to multiple Roadside Multihop Cells. All vehicles that enter into or leave this ad hoc network must pass one of the base stations, and are required to exchange information with the base station in the proposed scheme. Hence, the position of a vehicle can be precisely determined (in a small Roadside Multihop Cell) and tracked by base stations. On the contrary, the position of a mobile node in a general two-dimensional ad hoc network cannot be precisely determined, because such a mobile node can move freely.

The proposed scheme utilizes the Roadside Multihop Cell model to reduce overhead and improve connectivity. The basic idea is to use a Roadside Multihop Cell as a registration area. The mobility management scheme requires a vehicle to send a registration message whenever she enters into a new registration area. In the conventional scheme, the mobiles nodes have to send registration messages multihop away, since the border of the ad hoc network is k hops away, as Fig. 6 shows. However, using our model, the borders of a registration area are often within the radio range of base stations, hence the vehicle can send registration messages within 1 hop. Similarly, the service announcement messages (including information about the base station and the Roadside Multihop Cells) can also be sent within 1 hop, instead of k hops in the conventional scheme. When searching for a destination vehicle, a base station sends messages in a Roadside Multihop Cell that the destination will reside only. Thus, unnecessary messages are avoided and overhead can be reduced. Another advantage is that multiple base stations at the entrances of a Roadside Multihop Cell can cooperate to discover the connection to a vehicle that

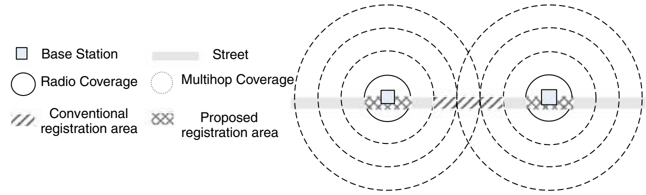


Fig. 6 The areas where registration is invoked (*shaded area*)

has registered to the cell. In this way, the connectivity can be improved without sending more messages.

Some Roadside Multihop Cells, e.g. Roadside Multihop Cell 2 (RMC_2) in Fig. 5 which consists of (BS_2, 2) only, have entrances where no base stations are installed. In such case, conventional scheme will be used to manage vehicles in such cells. However, with development of vehicular networks, we expect that many base stations will be set up and most Roadside Multihop Cells will have base stations installed at all of their entrances.

4 Mobility management operations

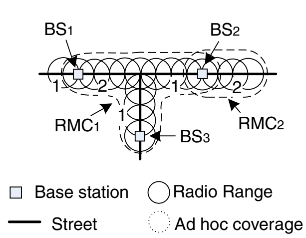
In this section, we describe the mobility management operations based on the proposed Roadside Multihop Cell, including service announcement, registration procedure and searching the destination. The mobility management operations can be integrated with any ad hoc routing protocol to provide mobile data service to vehicles.

4.1 Service announcement and registration

A service announcement is a management message broadcast by a base station to announce the mobility-support services, such as registration information. The service announcement is periodically broadcast within the radio range of a base station but not forwarded by vehicles. We are able to reduce overhead on service announcement thanks to the proposed Roadside Multihop Cell. All vehicles must pass a base station to enter into a Roadside Multihop Cell, and they should received at least one copy of the service announcement when they pass a base station.

The registration information is organized as a list of (d, $attr_{RMC}$), where d is the index number of next road and $attr_{RMC}$ includes attributes of a Roadside Multihop Cell that is on the next road d, such as an ID of the cell ID_{RMC} and distance to all base stations in the cell. Each time a base station sends out a service announcement, such a list is constructed and included in the service announcement.

Fig. 5 Roadside Multi-hop Cells



A vehicle should always cache the received service announcements and use the newest cached service announcement. When a vehicle is approaching or arrives an intersection and knows the next road, the vehicle should retrieve ID_{RMC} from the newest service announcement using the number of the next road. Note that for a vehicle with preplan trip paths, the next road has been decided before the vehicle arrives the intersection. Hence, the vehicle could register to the new cell as soon as it receives a service announcement. For a vehicle without such preplan equipments, the next road is unknown before the vehicle passes the intersection. In that case, the vehicle should cache the new service announcement and delay the registration until it passes the intersection.

If the ID of the new Roadside Multihop Cell is different from the old one, the vehicle realizes that it is entering into a new Roadside Multihop Cell and should initiate a *RMC registration* process. A *RMC registration* is only handled between a vehicle and base stations without any affect on the home agent. A RMC registration request is sent by a vehicle to a base station which contains the ID of the new Roadside Multihop Cell that the vehicle wishes to register. At that time, the vehicle should be still in the radio range of the base station. Hence, the registration request is sent via single hop. If the vehicle happens to be out of the radio range of the base station when or after sending the registration request, it will not receive a response for the registration. Then, the vehicle should send the RMC registration via multihops again.

The RMC registration is handled between vehicles and base stations to manage the movement of vehicles between Roadside Multihop Cells. Based on RMC registration and connection status, a vehicle decides when to send an MIP registration message to register a new foreign agent. If a vehicle sends a RMC registration message for the first time, i.e. the vehicle does not register to any RMC yet, the vehicle should later send an MIP registration and register the current base station as a foreign agent. A vehicle also triggers an MIP registration when the vehicle gets better connection to a new base station, for example, the vehicle is closer to a new base station than the old base station or the connection to the old base station has been lost. A vehicle which participates active communication monitors its distance constantly. When the distance to the next base station is shorter than the distance to the old base station, the vehicle could try to send a route discovery message to the next base station. If a short path is discovered, the vehicle registers the next base station as the new foreign agent. For an inactive vehicle, i.e. a vehicle which does not send or receive any message, it is not necessary to maintain a path or monitor the distance. When a message arrives for a vehicle which is inactive or there is no valid *fresh* route to the vehicle, then all base stations in the Roadside Multihop Cell search for a route. (This multi-agent operation is described in more details in Section 4.2). If a better connection, i.e. a shorter path is discovered to a new base station, the vehicle should send an MIP registration message to register the new base station as a foreign agent.

The broadcast interval of service announcement depends on the maximum speed of vehicles. In order to let all vehicles receive at least one copy of service announcement, the broadcast interval should not be larger than r/v_{max}, where r is the radio range and v_{max} is maximum speed of vehicles. Assume the radio range is 500 m, the minimum broadcast interval is 5.6 s for $v_{max} = 200$ mph.

The overhead of service announcement within a RMC is defined as the number of bytes sent for service announcement within a time unit, which depends on the broadcasting frequency and size of service announcement. Assume a broadcast interval T_b and size of service announcement S_s, the overhead of service announcement is $S_s/T_b = S_s \cdot v_{max}/r$. This overhead does not depend on the size of ad hoc subnet. Hence, It is constant and scalable.

The overhead of registration within a RMC is defined as the number of bytes sent for registration within a time unit, which depends on the transiting rate of vehicles (the number of vehicles passed by in a time unit) and the size of registration messages. Transiting rate equals the number of vehicles leaving/entering a RMC in a time unit. We assume transiting rate of vehicles at a base station is λ. The same amount of RMC registration request/response messages are sent/received by the vehicles. We assume that S_{rq} is the size of a RMC registration request, S_{rp} is the size of a RMC registration response, S'_{rq} is the size of an MIP registration request and S'_{rp} is the size of an MIP registration response. We also define β to express the relative frequency of sending MIP registration messages compared with that of sending RMC registration messages. Note that a vehicle sends a RMC registration request whenever it changes a RMC but an MIP registration request may not be sent for inactive vehicles. Hence, the overhead of registration is $\lambda \cdot ((S_{rq} + S_{rp}) + (S'_{rq} + S'_{rp}) \cdot \beta)$.

4.2 Multi-agent operations for searching destination

Multi-agent operation in the proposed Roadside Multihop Cell scheme is to search all possible connections to a vehicle. After successful registration of a vehicle, all packets that address the home address of the vehicle will be forwarded to the base station that the vehicle has registered on. When a packet arrives at a base station and its destination is a registered vehicle, the base station checks the routing information to deliver the packet. If the routing information is fresh, the base station uses the routing information to forward packets. Otherwise, the base station has to search a connection with the destination. Multi-agent operation is invoked when searching a destination.

Fresh routing information is such information that has been used by the base station to forward packets to a vehicle and is assume to be still valid at this time. For example, the routing information in AODV (Ad hoc On-Demand Distance Vector) routing protocol is a valid path in the routing table for the destination. The path to a destination in AODV is discovered on-demand and will expire very soon in a high mobile network. Hence, before the path expires or routing errors are reported for the path, we assume the path can reach the destination.

In case a base station does not have fresh routing information to the destination, the base station broadcast signaling message to search the destination. At the same time, the base station sends a multi-agent searching message to all base stations that at the border of the Roadside Multihop Cell which the destination has registered on. Upon receiving a multi-agent searching message, a base station broadcasts the signaling message in the required Roadside Multihop Cell to search the destination. As the example in Fig. 7, when the destination vehicle is actively communicating, a new path to the destination can be discovered by BS2 quickly after the path between the destination and BS1 has broken.

Once a new path between the vehicle and a new base station is discovered, the new base station becomes temporary agent of the vehicle. The connection to the temporary agent is immediately used for transmitting packets, but the temporary agent will be registered as a foreign agent until it is stable enough. When a new path is discovered, the old foreign agent is asked to forward the packets for the vehicle to the temporary agent, which will forward packets to the vehicle via the vehicular ad hoc network. If the connection between the vehicle and the temporary agent exists for a duration of at least T_e, the vehicle will send a request to register the temporary agent as the new foreign agent.

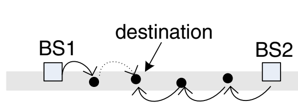


Fig. 7 Multi-agent operation for searching a destination in a Roadside Multihop Cell

Then, the packets to the vehicle will be forwarded from the home agent to the new foreign agent directly.

4.3 Broadcasting in a Roadside Multihop Cell

Broadcasting in a Roadside Multihop Cell is different from the conventional broadcasting scheme in that messages are flooded between several base stations along the roads, instead of in an area where a base station is at the center. As we discussed in Section 3, the signaling message for searching a destination should not be flooded outside of a Roadside Multihop Cell where the destination has registered on, because they will never reach the destination.

To realize the broadcasting in a Roadside Multihop Cell, a broadcast message carries a ID of a Roadside Multihop Cell ID_{CRMC}. When ID_{CRMC} is zero, the message is treated as a conventional broadcasting message, i.e. it is forwarded by every vehicle till the TTL fields decrease to zero. When ID_{CRMC} is a non-zero value, the message is forwarded by the vehicle that has registered on the Roadside Multihop Cell with the same ID value only. Therefore, the broadcast message is dropped by the first vehicle that does not register on the Roadside Multihop Cell or when the TTL field decreases to zero. This makes the message is flooded in a certain Roadside Multihop Cell only.

The proposed broadcasting may have a problem in the radio range of a base station. In the radio range of a base station, a vehicle is switching its registration to a new Roadside Multihop Cell. However, the vehicle may be only one that can forward broadcast messages to its old Roadside Multihop Cell. If the vehicle does not forward broadcast messages that carries the ID of the old Roadside Multihop Cell, the messages may not reach the vehicles in the old Roadside Multihop Cell. Hence, a vehicle should set a timer after registering to a new Roadside Multihop Cell. The vehicle forwards packet for the old Roadside Multihop Cell until the timer expires.

The proposed broadcasting scheme avoids flooding messages on the road that the destination will not reside in, hence the overhead is reduced. Assuming that a Roadside Multihop Cell has at most k hops and the number of roads that merge at the intersection where the base station is installed is n. In the conventional scheme, a signaling message for searching a destination is forwarded at most kn times. Using the proposed Roadside Multihop Cell, the signaling message for searching the destination is forwarded at most d/r times, where d is the length of all roads in the Roadside Multihop Cell. Hence, the overhead is reduced by $\frac{kn-d/r}{kn}$.

5 Analysis of improvement on connectivity

The improvement on connectivity using the proposed Roadside Multihop Cell scheme is analyzed in this section. The connectivity between a vehicle and a base station is expressed as a function $P_m(x)$ in [23], which is the probability that a vehicle can reach a base station at distance x in at most m hops. Then, the probability that a vehicle is connected with a base station with exact m hops $P'_m(x) = P_m(x) - P_{m-1}(x)$. We estimate the improvement of connectivity based on $P_m(x)$.

The improvement of connectivity is calculated for a vehicle moving on a road with two base stations. Assuming base stations BS_1, BS_2 are at two ends of the road. When a vehicle is moving on this road, both base stations may be connected with the vehicle via multihop ad hoc networks. Without loss of generality, we assume that a vehicle has passes by BS_1 and has registered on BS_1. The distance between the vehicle and BS_1 is x. Then, the probability that the vehicle can reach BS_2 in at most $m-2$ hops is $P_{m-2}(d-x)$, where d is the distance between BS_1 and BS_2. When the number of hops between the vehicle and BS_2 is at most $(m-2)$, the vehicle will switch registration to BS_2 in the conventional Mutlihop Cell scheme. In this case, the connection can be discovered by the conventional Mutlihop Cell scheme and should not be considered as improvement of the proposed Roadside Mutlihop Cell scheme. The Roadside Mutlihop Cell scheme improves connectivity when the vehicle is disconnected from BS_1 and the number of hops between the vehicle and BS_2 is at least $(m-2)$.

The probability that the connectivity is improved at distance x is

$$\sum_{m=\lceil \frac{x}{r} \rceil}^{2\lceil \frac{x}{r} \rceil} \left(1 - P'_m(x)\right) \cdot \left(1 - P_{m-2}(d-x)\right) \qquad (1)$$

where $2\lceil \frac{x}{r} \rceil$ is the maximum hops between the vehicle and BS_1, $\lceil \frac{x}{r} \rceil$ is and the minimum hops between the vehicle and BS_1.

6 Simulation

In this section, we evaluate the performance of the proposed Roadside Multihop Cell scheme in a realistic environment through simulation. SUMO (Simulation of Urban MObility, [24]), a dedicated vehicular traffic simulator, is used to generate the realistic movement of vehicles in a trace file, containing vehicle location and time information. Then, the generated trace file is converted to the format that can be used by network simulator. QualNet, a professional network simulator, is used in this research to simulate and evaluate the performance of data communications between vehicles and hosts in fixed IP networks. The performance of the proposed Roadside Multihop Cell scheme is compared with the conventional Multihop Cell scheme in terms of mobility management overhead, data delivery ratio and throughput. The results show that the proposed Roadside Multihop Cell scheme reduced the mobility management overhead up to 63%, improve the data delivery ratio of CBR traffic up to 90% and throughput of FTP traffic up to 33% in our simulation results.

The simulation is implemented according to the highway system around west Des Moines area, where interstate highways and state highways make a grid-like architecture. The map (Fig. 8) and road data can be obtained from U.S. Census Bureau [25]. We finalize the road data and put base stations on intersections and along the road, averagely every 2 Km. The vehicles are instrumented with wireless devices and implement ad hoc routing protocol and mobility management protocol. Data traffic is generated between a host in the fixed IP network and vehicles that are moving along the highway. The performance of data communication is evaluated and analyzed through simulation. Next, we briefly introduce SUMO and QualNet at first, then the simulation configuration and results are presented.

6.1 Vehicle traffic simulation

SUMO (Simulation of Urban MObility) [24] is a microscopic, space-continuous road traffic simulation package. Microscopic means that the simulator models the

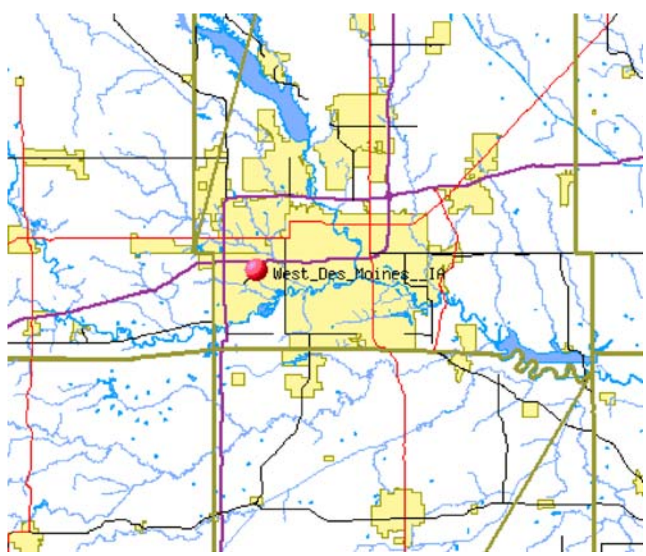


Fig. 8 The map of west Des Moines area

movement of every single vehicle on the street, mostly assuming that the behavior of the vehicle depends on both the vehicle's physical abilities to move and the driver's controlling behavior. The common behaviors, such as changing lanes or stop before the stop signs and traffic lights, are all supported in SUMO. Although it is primarily designed for urban mobility simulation, as implied by the name, it can be used for highway mobility simulation as well.

The vehicular network that we study in the simulation is an intersection area of highway, which is the basic component in the model of vehicular network that we presented in Section 3. As shown in Fig. 9, there is one real intersection and four virtual intersections. One base station is installed at each intersection. This vehicular network presents a typical data communication environment between vehicles and the hosts in fixed IP networks.

The parameters of this vehicular network follows the typical scenarios on highway. The speed limit of the roads are set as 70 mph (31.3 m/s). Vehicles are generated at Road5 and Road6 and move at a speed fluctuant around 70 mph, according to their behavior factors. When approaching the intersection, vehicles may go straight or make a turn with equal probability. The actual number of vehicles on the road is described as *traffic density*, which is the average number of vehicles that occupy 1 kilometer of road space. In our simulation, we reflect vehicle traffic density by vehicle generation rate. A moderate traffic density is simulated by a vehicle generation rate 0.2 vehicle/s, i.e. generating a vehicle every 5 s. It reflects a traffic density of 6.4 vehicles per kilometer. A high traffic density is simulated by a vehicle generation rate 0.5 vehicle/s, i.e. generating a vehicle every 2 s. It reflects a traffic density of 16 vehicles per kilometer.

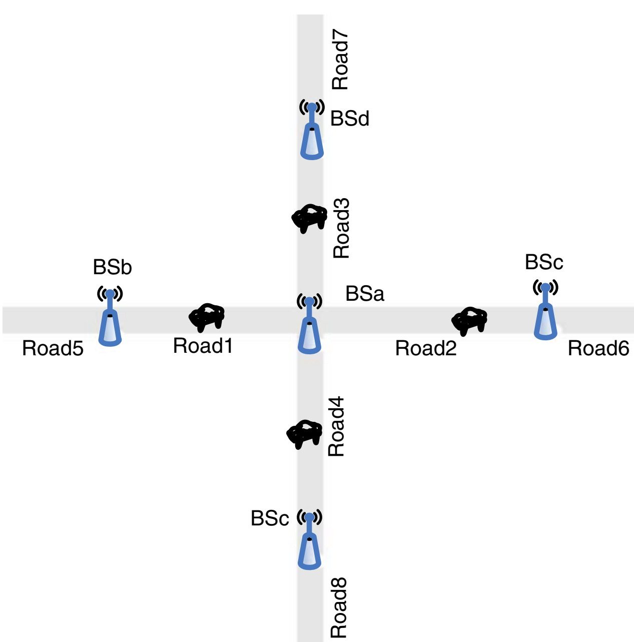


Fig. 9 The demonstrative vehicular network

A vehicle traffic scenario with the parameters described above is simulated by SUMO. Upon finishing simulation, a trace file is generated with vehicles' positions on each street and each lane at every time step (1 s). The trace file is then converted to the node position file which is used by QualNet. The data communication is performed based on the node position file by QualNet.

6.2 Data communication simulation

QualNet [26] is a network modeling software that evaluate performance of data networks through simulation. QualNet provides most popular network models from physical layer to application layer. The parameters of data communicated that is used in our simulation is listed in Table 1. The specific models and parameters that are used in our simulation are described as below.

At physical layer, the high speed fading model is used to model fading with high speed movements. In this model, fading Gaussian components dynamically determine fading values. Hence, a realistic channel status for the data transmission between high speed vehicles are modeled.

IEEE 802.11a is used as MAC protocol and independent basic service sets (IBSS) are constructed for data communication at MAC layer. IEEE 802.11a is the base on that FCC (Federal Communications Commission) is

Table 1 Parameters used in QualNet simulation

Channel frequency	2.4 GHz
Propagation pathloss model	Two ray
Propagation fading model	High speed
Radio range	424 m
MAC protocol	IEEE 802.11a
RTS/CTS	Always
802.11 short packet transmit limit	7
802.11 long packet transmit limit	4
CBR packet size	512 Bytes
CBR packet generation interval	1 S
AODV local repair	NO
AODV hello message interval	1 S
AODV allowed hello message loss	3
AODV request retry limit	2
Mobile IP advertisement TTL in conventional Multihop Cell	3
Mobile IP advertisement TTL in Roadside Multihop Cell	1

developing the future MAC specifications for vehicular networks. Combining with high speed fading model, a realistic data communication environment for vehicular networks is used in our simulation.

AODV [27] is used as ad hoc routing protocol in our simulation. With the proposed Roadside Multihop Cell scheme or the conventional Multihop Cell scheme, AODV delivers packets between base stations and vehicles. When searching a connection to the destination is required, AODV broadcasts a request in ad hoc networks for the destination and uses the path for a short period if a path is discovered. If the path breaks before expiration, a routing error message will be reported to the sender.

To study the performance of data communication, we set up CBR (constant bit rate) and FTP traffic between a moving vehicle and a host in the fixed IP network in our simulation. By constantly sending out packets, CBR examines the capability of an scheme to discover the connectivity. However, most of main steam applications use TCP based connections, unlike the UDP based connection used in CBR. Therefore, we also evaluate FTP application, which uses TCP connections, to model the TCP based applications in our simulation.

In order to realize data communications in a hierarchical mobile network, a mobility management protocol has to be used to track the location of mobile nodes. Mobile IP is the most popular mobility management protocol in data networks. However, the conventional Mobile IP [21] provided by QualNet works with single-hop wireless subnets only. In our simulation, the Mobile IP functions of QualNet are extended to work with multihop ad hoc subnets,[1] which provides functions of the conventional Multihop Cell scheme. The proposed Roadside Multihop Cell scheme is also implemented in QualNet and compared with the conventional Multihop Cell scheme in our simulation. Configuration of conventional Multihop Cell and the proposed Roadside Multihop Cell are described below, based on the vehicular network in Fig. 9.

When using the conventional Multihop Cell scheme, each base station constructs a conventional Multihop Cell around its intersection. The radius of a conventional Multihop Cell is 3 hops in our simulation. In the vehicular network as Fig. 9, 5 conventional Multihop Cells are constructed for data communication. When using the proposed Roadside Multihop Cell scheme, BS_a and each of other four base stations form a Roadside Multihop Cell with base stations installed at all entrances. Besides, each of the four base stations, except BS_a, forms an Roadside Multihop Cell with some entrances do not have base station installed. In this scenario, 8 Roadside Multihop Cell are constructed for data communications.

[1]More details can be found in [19].

6.3 Simulation results analysis

6.3.1 Study the improvement of connectivity discovery

In order to exam the capability of the proposed Roadside Multihop Cell scheme and conventional Multihop Cell scheme, we set up a CBR traffic between a moving vehicle and a host in the fixed IP network for 50 s (other parameters are listed in Table 1). The host in the fixed IP network is set as the sender and a moving vehicle is set as the receiver. The vehicle was moving from BS_b to BS_a on Road1 during the data traffic. The packets that are sent to the home address of the moving vehicle are intercepted and forwarded by the home agent of the vehicle. The intercepted packets are forwarded to the current foreign agent (on a base station) that the vehicle has registered on. Then, the foreign agent delivers packets to the vehicle.

The summarized results of simulation are shown in Table 2. The proposed Roadside Multihop Cell scheme improved CBR data delivery ratio by 83.5% with total management overhead reduced by 39.2%. The reason behind the improved data delivery ratio is clearly shown in Fig. 10. By examining the connection status between the moving vehicle and the agents at both ends of the road, it is clear that the vehicle is connected to agent BS_b at first. With moving, the vehicle is disconnected with the agent BS_b and connected to agent BS_a.

In the conventional Multihop Cell scheme, foreign agents could deliver packets to the vehicle only at the beginning or at the end of duration. In the middle of the duration of data traffic, the vehicle moves to the middle of Road1, where the vehicle is disconnected to the registered agent BS_b but cannot register on the agent BS_a, because the vehicle can only register on the new agent when a service announcement is received and the distance to the new agent is at least 2 hops smaller than that to the old agent. Even though the old agent BS_b has received the route error report message of AODV, the agent BS_a which is connected with the vehicle will not discover the connection actively. As the result, 67% CBR packets are lost, although the disconnection occupies only 12% of the data traffic duration.

Using the proposed Roadside Multihop Cell scheme, the vehicle actually registers to a Roadside Multihop Cell, which includes the intersections where BS_a and

Table 2 Comparison of the conventional Multihop Cell (CMC) scheme and the proposed Roadside Multihop Cell (RMC) scheme with CBR traffic

Metric	CMC performance	RMC performance	Improvement
Overhead of advertisement (Kbps)	838.477	184.852	78.0%
Overhead of registration (Kbps)	249.188	169.875	31.8%
Overhead of searching destination (Kbps)	1602.19	1280	20.1%
Total management overhead (Kbps)	2689.855	1634.727	39.2%
Number of packets dropped by MAC protocol	172	44	74.4%
CBR data delivery ratio (%)	33.3	61.1	83.5%
CBR data delivery delay (s)	0.010	0.016	−0.006
CBR data delivery jitter (s)	4.52	1.39	3.13

BS_b are installed and Road1 between them. Upon the vehicle is disconnected from agent BS_b, all agents (BS_b and BS_a) of the Roadside Multihop Cell are invoked to search the vehicle on Road1. As shown in Fig. 10, the connection between the vehicle and agent BS_a is discovered quickly and packets are savaged by the discovered connection. This multi-agent operation contributes the 83.5% improvement on data delivery ratio of CBR traffic, which is shown in Table 2.

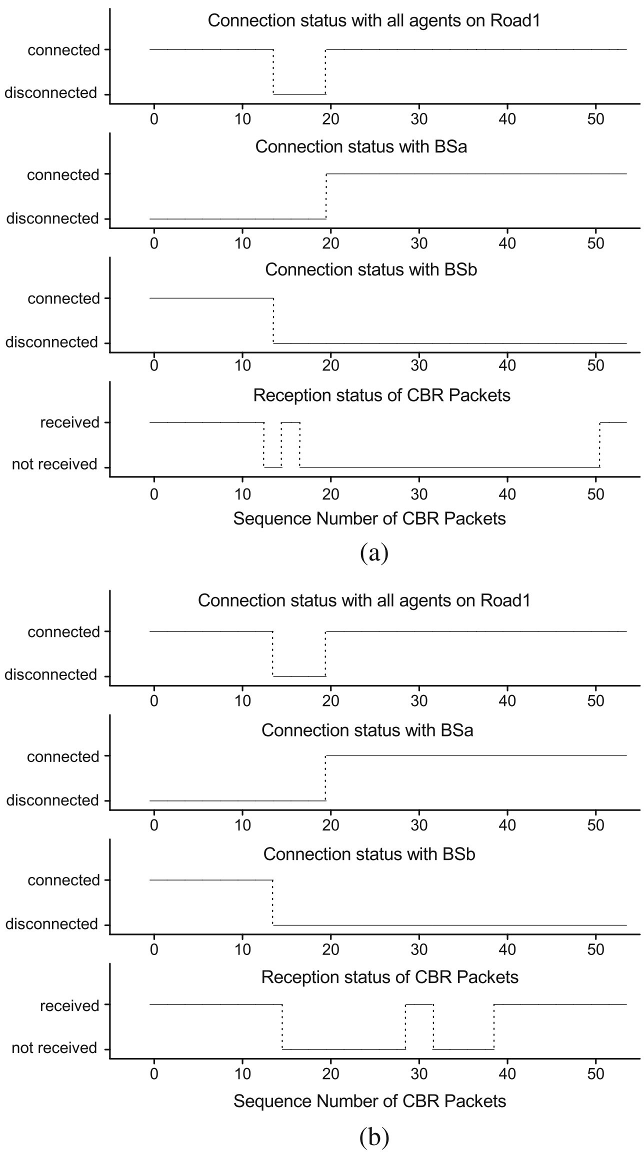


Fig. 10 Comparison of CBR reception status with connection status to agents. **a** Conventional multihop cell. **b** Roadside multihop cell

In Table 2, the results also show that the proposed Roadside Multihop Cell reduces the total mobility management overhead by 39%, including a significant saving by 78% on service announcement, 31% on registration and 20% on searching a destination. The results also show that the proposed Roadside Multihop Cell scheme has comparable CBR data delivery delay and smaller CBR data delivery jitter.

6.3.2 Study the impact of management overhead

The improvement on mobility management overhead is attributed to the single-hop service announcement, single-hop registration messages and elimination of unnecessary messages for searching the destination in the proposed Roadside Multihop Cell scheme. The conventional Multihop Cell scheme produces more mobility management overhead and hence suffers heavier transmission collision at MAC layer. As shown in Table 2, the number of packets dropped by MAC protocol[2] using the conventional Multihop Cell scheme is higher than that using the proposed Roadside Multihop Cell scheme.

To evaluated the impact of management overhead on data communication, we set up one downlink CBR data traffic and one uplink CBR data traffic, both with a duration of 50 s. The downlink and uplink CBR traffics are implemented asynchronously at first, using conventional Multihop Cell scheme or Roadside Multihop Cell scheme. Then, they are set up on two vehicles and are implemented simultaneously, using conventional Multihop Cell scheme or Roadside Multihop Cell scheme. To eliminate the impact of different connection

[2]The dropped packets are not necessarily packets of data traffic.

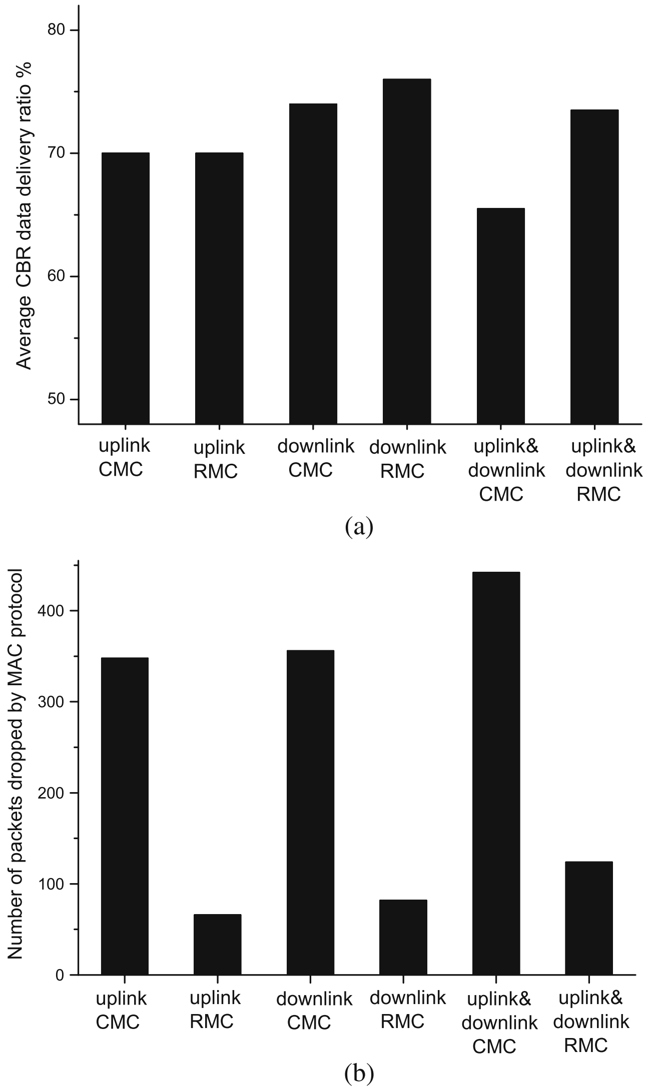


Fig. 11 Study of impact of mobility management overhead. **a** Comparison of average CBR traffic data delivery ratio under different scenarios. **b** Comparison of number of packets drop by MAC protocol

discovery capability of conventional Multihop Cell scheme and the proposed Roadside Multihop Cell scheme, we select vehicles that are connected to the registered agent during the data traffic duration. Then, the results for the impact of overhead are shown in Fig. 11.

The results in Fig. 11a show that the CBR data delivery ratios are both 70% for conventional Multihop Cell scheme or Roadside Multihop Cell scheme in the single uplink data traffic scenario. In the single downlink data traffic scenario, the CBR data delivery ratios are slightly different with 74% for the conventional Multihop Cell scheme and 76% for the Roadside Multihop Cell scheme. When the uplink and downlink data traffics are implemented at the same time, the average data delivery ratio using the proposed Roadside Multihop Cell scheme, 73%, equals the average number of separate uplink and downlink data traffic scenario. It shows that the data delivery ratio is not impacted. When using the conventional Multihop Cell scheme, the average CBR data delivery ratio is 12.5% less than the average number of separate uplink and downlink data traffic scenario. The reason can be explained by the transmission collision degree at MAC layer, which is reflected by the number of packets dropped by MAC layer in Fig. 11b. The figure shows that the conventional Multihop Cell scheme produces a large number of mobility management overhead and the data delivery ratio is impacted due to heavy collisions in MAC layer.While the proposed Roadside Multihop Cell scheme produces much less mobility management overhead and has small impact on data delivery ratio.

6.3.3 Study the performance with hybrid data applications and high vehicular traffic density

To study the performance of data communication more comprehensively, we set up CBR and FTP applications in the vehicular network with high traffic density, i.e. using vehicle generation rate 0.5 vehicles/s. The data packets generated by FTP application have a length of 512 bytes and a duration of 50 s. The CBR application and FTP application are assigned to two different vehicles and are implemented at the same time.

Table 3 Comparison of the conventional Multihop Cell (CMC) scheme and the proposed Roadside Multihop Cell (RMC) scheme with CBR and FTP traffic in a vehicular network with dense traffic

Metric	CMC performance	RMC performance	Improvement
Overhead of advertisement (Kbps)	1596.62	184.602	88.4%
Overhead of registration (Kbps)	483.188	284.625	41.1%
Overhead of searching destination (Kbps)	6397.19	2643.44	58.7%
Total management overhead (Kbps)	8477	3112.66	63.3%
Number of packets dropped by MAC protocol	859	112	87.0%
CBR data delivery ratio (%)	44	84	90.9%
CBR data delivery delay (s)	0.228	0.0208	0.207
CBR data delivery jitter (s)	1.729	0.368	1.361
FTP throughput (Kbps)	166.443	222.092	33.4%

The results are shown in Table 3. The improvement on the performance is even higher in a vehicular network with high traffic density, compared with the results in Table 2 in a vehicular network with moderate traffic density. The proposed Roadside Multihop Cell improved the data delivery ratio of CBR traffic by 90% and the total management overhead is reduced 63.3%. The throughput of FTP traffic is also 33% higher than that using conventional Multihop Cell scheme. The results show that the proposed Roadside Multihop Cell scheme is scalable and outperforms the conventional Multihop Cell scheme in both vehicular networks with moderate traffic density or high traffic density.

By analyzing the simulation results above, the proposed Roadside Multihop Cell scheme is shown to outperform the conventional Multihop Cell scheme with significantly reduced mobility management overhead, higher data delivery ratio and better scalability. We have tested the RMC scheme for various distances between base stations and the results are similar. To save space, we did not present the results in this paper.

7 Conclusions

This paper proposed a novel mobility management scheme for integration of vehicular ad hoc network and fixed IP networks. The paper is inspired from the observation of the unique characteristics of vehicular networks, which introduce problems to the conventional mobility management schemes when they are deployed in vehicular networks. After analyzing the problems of the conventional mobility management scheme, we propose a Roadside Multihop Cell scheme. The proposed scheme manages the vehicles based on street layout instead of the distance between vehicles and base stations in the conventional schemes. We simulate the proposed scheme in SUMO (a vehicular traffic simulator) and QualNet (a data network simulator). Analysis and simulation results show that the mobility management overhead is reduced up to 63% and the data delivery ratio is improved up to 90% using the proposed mobility management scheme.

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